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APPLICANT : Nicholas R. White
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FOR : "METHOD AND FINE-CONTROL COLLIMATOR FOR ACCURATE COLLIMATION AND PRECISE PARALLEL ALIGNMENT OF SCANNED ION BEAMS"
EXAMINER : Nikita Wells
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Date: May 19, 2005

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MARKED UP VERSION OF AMENDED SPECIFICATION SUBMITTED
PURSUANT TO 37 C.F.R.1.121(b)(1)(ii)

Commissioner for Patents
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Sir:

Applicant, in fulfillment of and in accordance with the requirements of 37 CRF 1.121(b)(1)(ii), hereby submits a marked-up version of the present amendments to the Specification which appear at the following locations:

Page 12, lines 7, 9, 11, 14, 16, 18 and 20.

Page 13, lines 1, 4, 6, 7, 8, 9, 10, 12 and 14.

Page 20, lines 5, 7, 11 and 19.

Page 21, lines 6 and 11.

Page 23, lines 12 and 13.

Page 24, lines 5, 10, 13 and 19.

Page 25, line 18.

Page 26, lines 9 and 22.

Page 27, line 13.

Page 30, lines 19 and 20.

Page 31, line 4.

Page 37, line 23.

Page 38, lines 4, 12 and 20.

Page 39, line 21.

Page 41, line 2.

Page 42, line 24.

Page 44, line 3.

Page 45, lines 11, 22 and 23.

Page 46, lines 2, 8 and 11.

Page 47, line 11.

Page 48, lines 2 and 4.

Page 50, line 12.

REMARKS

Via the Notice Of Allowance And Fee(s) Due mailed March 8th, 2005 for the above-identified application, the Examiner of record has made a requirement for a new corrected formal Drawing because the originally submitted figures were not numbered consecutively.

This Examiner-imposed requirement has thus indirectly and concomitantly demanded that applicant now also amend and renumber each specific reference to any of the individual original figures within the Specification such that the figure numbers recited in the written text will correspond to the enclosed consecutively numbered Replacement Sheets constituting new substitute Figs. 1-15 respectively. It is for this reason, and solely for this reason alone, that the present amendments to the Specification text are made.

Respectfully submitted,

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modifying the waveform that is applied to the beam scanner in response to the measured dose rate such that the errors in dose rate relative to a pre-defined desired dose profile are substantially reduced.

BRIEF DESCRIPTION OF THE FIGURES

The present invention is better appreciated and more easily understood when taken in conjunction with the accompanying drawing, in which:

Fig. ~~A~~ 1 shows a prior art Cartesian multipole lens used for controlling the uniformity of continuous ribbon beams;

Fig. ~~B~~ 2 shows a sectional view of a prior art collimator magnet whose pole contains movable ferromagnetic rods;

Figs. ~~1A and 1B~~ 3 and 4 show a perspective view and a cross-sectional view looking in the direction of the beam of a fine-control collimator/steerer construct suitable for correction of parallelism in a charged particle beam in accordance with the present invention;

Fig. ~~2~~ 5 shows the magnetic field profile caused by exciting individual pairs of wire deflectors;

Fig. ~~3~~ 6 shows the magnetic field gradient caused by exciting individual pairs of wire deflectors;

Fig. ~~4~~ 7 shows a method of connecting the coil deflectors of Fig.1 to allow y-axis steering control;

Fig. ~~5~~ 8 shows a general layout of the scanning and implanting section of a first conventionally known ion implantation system which can be modified to include a fine-control collimator of the present invention;

Fig. ~~6~~ 9 shows a general layout of the scanning and implanting section of a second conventionally known ion implantation system which can be modified to include a fine-control collimator of the present invention;

Fig. ~~7~~ 10 shows a beam alignment plate, of which two are used in a preferred embodiment of this invention.

Fig. ~~8A and 8B~~ 11A and 11B show the current waveform that can be observed as the beam is scanned across and through the holes of the alignment plate of Fig. ~~7~~ 10;

Fig. ~~9~~ 12 illustrates how the non-parallelism of the beam trajectories may be calculated from the timing information obtained from the waveform of Fig. ~~8~~ 11;

Fig. ~~10~~ 13 shows an example of a non-parallel ion beam and its correction using only four pairs of deflectors;

Fig. ~~11~~ 14 shows a flow diagram of the method according to this invention for concurrent control of parallelism and uniformity of a scanned ion beam; and

Fig. ~~12~~ 15 shows a flow diagram of a preferred method of measuring the parallelism of a scanned ion beam.

DETAILED DESCRIPTION OF THE INVENTION

The present invention comprises a method for accurate collimation and parallel alignment of a scanned ion beam; and provides an unique precision instrument, a fine-control collimator, for accurately adjusting and controlling the parallelism of the trajectories for the charged particles in a scanned ion beam.

Conventionally known and previously existing hybrid parallel-scanned ion implantation apparatus and systems typically have a device which functions as a coarse collimator and which

The program TRANSPORT may also be used to design a system in which this aberration is controlled.

A first modified construction

A first candidate able to be structurally modified as a 'fine collimator' is the prior art device shown by Fig. ~~A~~ 1. This device can be electrically excited in a manner that is mirror-symmetric, and is capable of generating the spatially varying B_y components. As shown by Fig. ~~A~~ 1, the device has a symmetrical paired set of simple electromagnets presented as a row of wire-wound ferromagnetic poles set above and below the beam, which are mounted to a surrounding ferromagnetic yoke. With a resolution determined by the pitch of its multiple poles, this device can create an arbitrary spatially varying magnetic field in the y-axis direction. However, the device of Fig. ~~A~~ 1 does not intrinsically generate a uniform x-axis component of magnetic field.

This desired feature and capability, however, could be generated separately by the addition of a magnetic beam steering apparatus; or, alternatively, by modifying the conventional structure to incorporate additional electrical coiled windings suitable for this purpose.

A second modified construction

Another conventionally known device which can be structurally modified to function as a 'fine collimator'and then generate the y-axis component of the varying magnetic field is shown by Fig. ~~B~~ 2. Presuming that the ion implanter system uses a dipole magnet to achieve coarse collimation for the scanned ion beam, then the necessary modification is that one or more sets of movable rods be installed in one or both poles, thereby creating a spatial zone in which a varying B_y component is superimposed on the static B_y component, which deflects the ion beam through a total angle of (typically) between 30 and 90 degrees. This spatial zone can achieve the desired

improvement in parallelism and fine collimation in the x-axis direction. Symmetrical arrangements minimize unwanted variations in B_x; but, in particular instances, asymmetrical arrangements may be acceptable. However, a separate device to remove y' errors is again required in all asymmetrical structures.

It will be recognized and appreciated, therefore, that although the structures and devices illustrated by Figs. ~~A~~ 1 and ~~B~~ 2 respectively are conventionally known and commonly used, the structural modifications described herein and the adaptation and use of the modified constructions have not previously been conceived, or considered, or functionally employed.

III. A Preferred Fine-Control Precision Instrument

An important aspect of the present invention is the novel and unique precision instrument and preferred embodiment of the fine-control collimator, as is illustrated by Figs. ~~1A~~ 3 and ~~1B~~ 4 respectively. The fine collimator/steerer is situated upstream from the workpiece WP, which is to be implanted with the beam ions at a target plane TPI. As seen therein, the fine collimator/steerer10 appears as two substantially similar subassemblies 40 and 140, each of which is spaced from the other at a pre-chosen gap distance. Within the two subassemblies 40 and 140 are two ferromagnetic bars 20 and 120, each of which is linearly sized to be somewhat longer than the x-axis or breadth dimension of the scanned ion beam 71; and each bar 20 and 120 is oriented to lie parallel to and at a pre-chosen gap distance 44 from the other.

Each ferromagnetic bar 20 and 120 serves as a linear support around which a plurality of individual wire windings are orthogonally placed at a number of predetermined and different locations as coil deflectors 22 and 122. Each ferromagnetic bar and its multiple wire windings thus form an axially aligned series of independent, separated, and adjacently located coil

error variation of parallelism is sufficiently small for a particular construct or embodiment, that a relatively large pitch for the individual coil deflectors becomes acceptable.

The Generated Magnetic Fields:

Also included as part of the overall fine collimator/steerer assembly are on-demand electrical controls (not shown) for introducing and passing electrical energy of variable amperage independently through each individual and adjacently positioned coil deflector 22 and 122 which is orthogonally disposed along the linear length of the support bars 20 and 120. When provided with electrical energy of an appropriate or desired amperage, each adjacently positioned energized coil deflector 22 and 122 independently generates a magnetic potential difference of limited breadth and an individually adjustable magnetic field gradient which extends orthogonally from each ferromagnetic bar, the field having a controllable gradient in a region of limited breadth. The magnetic field is illustrated by Fig. ~~2~~ 5 and the magnetic field gradient is shown by Fig. ~~3~~ 6.

It is intended that each energized deflector generates a local magnetic potential difference over its coil width, a gradient of limited breadth orthogonal to the winding along the x-axis direction; and oppositely situated pairs of energized deflectors arranged in reciprocal series on the two ferromagnetic bars will create a plurality of local magnetic potential differences of limited breadth in opposing directions along the x-axis dimension of the construct. This result cumulatively and collectively creates a fixed spatial zone between all the oppositely-situated pairs of deflectors in which the B_y field component changes - which then merges into two end regions of substantially constant field existing at each end of the support bars in the construct.

In this manner, the plurality of magnetic fields and adjustable magnetic field gradients generated by adjacently located pairs of opposing deflectors collectively sum to form a contiguous magnetic field and a spatially varying magnetic field gradient profile. The strength

each magnetic potential difference of limited breadth contributing to the overall magnetic field gradient profile within the fixed spatial zone can be individually altered at will (by varying the electrical amperage) to yield an adjusted and controlled broad magnetic field which has a pre-selected gradient profile and extends effectively over the entire breadth of the ion beam.

The particular construction of Figs. ~~1A~~ 3 and ~~1B~~ 4 generates within the rectangularly-shaped spatial passageway a magnetic field whose component B_y changes smoothly – *i.e.,* without abrupt differences. Excitation of a particular pair of oppositely-situated deflectors causes a *change* in B_y to be generated across the space between the particular pair of deflectors, and causes a change in an otherwise constant field B_y to be established in the spatial region on either side of this deflector pair. Fig. ~~3~~ 6 illustrates the electromagnetic effect caused by individual deflector pairs.

The Encompassing Spatial Passageway Through Which The Ion Beam Travels:

As illustrated by Figs. ~~1A~~ 3 and ~~1B~~ 4, the aligned series of independently and adjacently placed coil deflectors 22 and 122, (positioned on the linear ferromagnetic bars 20 and 120 and forming the first and second multideflector sequence arrangements 30 and 130) are congruent with (*i.e.,* coincide exactly when superimposed) and encompass the breadth dimension 42 of the spatial passageway 45 through which the scanned ion beam 71 travels in-situ. The multideflector sequence arrangements 30 and 130 are typically positioned by means of non-magnetic supports (not shown in Figs. ~~1A~~ 3 and ~~1B~~ 4) to lie in parallel and in aligned correspondence such that a preset separation distance ("h") exists and is maintained between each pair of oppositely-situated coil deflectors 22 and 122. The preset separation distance ("h") typically defines and dimensions two of the sides of the rectangularly-shaped, fixed spatial passageway 45 into which the desired magnetic field is generated and applied to the traveling ion beam.

It is essential that the size of the pre-chosen gap distance 44 existing between the two subassemblies 40 and 140 should be properly understood and appreciated. Each ferromagnetic bar 20 and 120 provides a ferromagnetic limit and fixed boundary at which the magnetic field lines are constrained to be orthogonal. The bars 20 and 120 are separated by a fixed spatial distance "2g". The multideflector sequence arrangements 30 and 130, however, occupy a part of this distance, and thus their preset separation distance is "h". It will be recognized that "h" is always quantitatively smaller than the fixed spatial distance "2g". Therefore, the size of the pre-chosen gap distance 44 for the construct 10 will thus never be greater than the fixed spatial distance "h" and, in some instances (*e.g.,* circumstances when vacuum walls intervene) may be significantly smaller than "h". In this manner, the spatial volume through which the charged particles of the scanned ion beam will travel (in the z-axis direction) is contained within and demarcated by the breadth distance 42 (representing the x-axis or wider dimension) and the pre-chosen gap distance 44 (representing the y-axis or narrower dimension) of the spatial passageway 45.

X-Axis Steering Controls:

It will be noted also that two additional pairs of wire windings forming steering coils 90 and 190 are individually disposed near the discrete ends of each ferromagnetic bar in the assembly shown by Figs. ~~1A~~ 3 and ~~1B~~ 4. These additional pairs of steering coils are independently connected to a source of electrical current in a manner similar to that of the coil deflectors 22 and 122, but the function of the steering coil pairs 90 and 190 is to provide overall x-axis steering control for the assembly. The pair of steering coils 90 at the ends of the bar 20 are electrically

connected in common – but in opposing senses - such that the net ampere turns through the two coils 90 is always zero in value. Similarly, the pair of steering coils 190 located at the ends of the bar 120 are electrically joined in common along the plane y=0. The function of these sets of steering coils 90 and 190 is to provide overall linear steering control for the scanned ion beam in the x-axis direction. Accordingly, steering coils 90 and 190 are referred to herein as "x-axis steering coils".

Y-Axis Steering Controls:

In some embodiments, the fine-control collimator optionally includes two thin-layer wire wrappings 91 and 191, which are shown only in Fig. ~~1B~~ 4. These thin-layer wire wrappings 91 and 191 are wound uniformly along and around substantially the entire linear length of each bar 20 and 120, and are located either within or over the cascade of adjacently placed coil deflectors forming the multideflector sequence arrangements. However, unlike all the coil deflectors, these two linear wire wrappings 91 and 191 are independently connected to a source of electrical current such that the amperage flow is *antisymmetrical* in the plane y=0. Accordingly, the intended function of these thin-layer linear wire wrappings is to provide the construct with the capability of controlling and steering the traveling ion beam in the y-axis direction; and thus are properly referred to herein as 'y-axis steering coils'.

Another alternate and optional means of providing the fine-control collimator with y-axis steering capability, but without creating or using the thin-layer linear wire wrappings 91 and 191, is to pass an antisymmetric electric current - in addition to the commonly shared deflecting electric currents - through all the deflectors. This can be accomplished by means of the structural arrangement shown in Fig. ~~4~~ 7.

As shown therein, a plurality of power supplies 60a,b,c are connected such that each supply provides electric current via a flow pathway which lies parallel to a particular matched deflector pair 22 and 122; but has a first commonly-shared current return line 64 from all the deflectors 22 and a second commonly-shared return line 66 from all the deflectors 122 which are individually connected to the terminals of a bipolar center-tapped power supply 61. By means of the power supply 61, a small additional potential difference is inserted between each pair of deflectors that are connected in parallel, and this potential difference unbalances the current flowing within each deflector pair. Within tolerances determined by the resistances of the individual deflectors, this arrangement generates a uniform x-axis directed field component capable of providing y-axis steering control for the construct. The use of the y-axis steering function and capability is described more fully below.

Using The Fine-Control Collimator:

Using the fine collimator/steerer illustrated by Figs. ~~1A~~ 3 and ~~1B~~ 4, an electrical current of known amperage is passed into each electrically joined pair of oppositely-situated deflectors (disposed upon the first and second multideflector sequence arrangements); and this amperage may be independently adjusted and controlled for each oppositely-situated pair of coil deflectors.

In addition, the individual pairs of oppositely-situated x-axis steering coils located closest to the ends of the ferromagnetic support rods may be positioned to lie just beyond the confines of the scanned ion beam width; and the end portions of each support bar can be increased in length beyond the last of the coil deflectors by a linear extension sufficient to ensure that the electromagnetic effects of the ferromagnetic bar ends on the distribution of the contiguous magnetic field (generated by the deflectors and applied to the scanned ion beam) are insignificant. The length of such bar end extensions will typically be at least twice the size of the

The total gap between the ferromagnetic bars is 2g. The number of ampere-turns in each coil nI is given by

$$nI < \frac{0.01g}{\mu_0 L_m}\sqrt{\frac{2MV}{q}}$$

IV. The Intended Locale For And Purposes Of The Fine-Control Collimator

Intended Locale:

A proper setting and intended environment for the present invention is within a hybrid scanning ion implantation apparatus and system. By definition and structure, such devices typically comprise: a source ("S") of charged particles traveling as an ion beam ("IB"); at least one dipole magnet (not shown) for separating a desired species of ions from impurity species; a scan device ("SD") for scanning the charged particles and generating a scanned ion beam ("SIB"); a coarse collimator ("CC") device (which may or may not be formed as a dipole magnet) for rendering the scanned beam approximately parallel or within about +/- 1 degree; a single, large Faraday cup ("FC"); and a targeted plane for implantation ("TPI") suitable for introducing the charged particles of the scanned ion beam into a prepared workpiece ("WP"), such as a silicon wafer, which is passed orthogonally through the scanned beam – *i.e.,* in the y-axis direction.

In all instances, the fine-control collimator comprising a part of the instant invention is intended to be used solely and exclusively with the charged particles of a scanned ion beam to improve their collimation. This is shown by Figs. ~~5~~ 8 and ~~6~~ 9 respectively.

Fig. ~~5~~ 8 illustrates the conventional use of a coarse collimator device in the form of a dipole magnet within a previously known hybrid scanning implantation system, but this now has a fine-control collimator portion 51 (formed of movable pole pieces) installed at the dipole magnet's

point of exit . This improved arrangement results in a system capable of correcting errors in collimation in x', but would require an additional device or other correction means in order to rectify errors in y'.

Fig. ~~6~~ 9 illustrates the alternative placement and use of a fine-control collimator/steerer as a discrete and independent construction located adjacent to the coarse collimator (dipole magnet) in order to provide fine collimation for the implantation system - *i.e.,* to remove substantially the remaining errors in both x' and y'.

Purposes and goals:

The purposes and goals of the unique precision collimator construct comprising a part of the instant invention may be more easily understood and better appreciated with reference to the coordinate system framework identified above, and are as follows:

(i) The time averaged current per unit length in the x-axis direction is typically desired to have a tightly controlled ion density profile, usually uniform, but under some circumstances deliberately non-uniform.

(ii) The beam direction is typically desired to be constant. Thus, the ion beam is "parallel scanned"; and it is desired to tightly control the parallelism and alignment of the charged particle trajectories in the z-axis direction.

(iii) It is desired that the instantaneous shape of the beam be independent of the x-axis coordinate of its centroid.

V. The Mode and Manner Of Increasing And Controlling Parallelism

The following discussion of the mode and manner for increasing and controlling parallelism of a scanned ion beam speaks mainly to error variations in the direction of the local

For purposes of future clarity and completeness, the texts of U.S. Patent Nos. 5,180,918; 6,313,474; and 6,696,688 are explicitly incorporated by reference herein.

A scanned ion beam's non-parallelism may be measured by these and other conventionally known methods. Preferably, however, a particular method for establishing the proper beam axis should be performed before bringing any of the conventional techniques for measuring non-parallelism to bear. Accordingly, such a procedure is described in detail below.

A Process For Establishing The Proper Beam Axis:

The z-axis during implantation is the intended direction of travel for the ion beam. The z-axis can be defined within the system's apparatus by means of a pair of reference marks, but preferably is defined by providing a fixed mount for an optical device which comprises a collimated light source and a means of inspecting the direction of the light. Such an optical device may be an autocollimating telescope, or a laser, or a combination of these.

It is desirable to pass the workpiece substrate for implantation through the ion beam at a tightly controlled angle. Noting that a bare silicon wafer is highly reflective, one can adjust the angle at which a silicon wafer is mounted at the plane of implantation until it reflects the reference light beam back on its initial path - at which point the wafer is mounted precisely normal to the z-axis at the plane. This procedure provides and defines an "axis of parallelism". Autocollimating telescopes are commercially available, and aligning reflective surfaces normal to an axis is their intended function and use.

Having thus defined an axis of parallelism as well as aligned the targeted mounted holder of silicon wafers until it can hold a reference wafer precisely normal to the z-axis, one now measures the direction of the ion beam with respect to this axis of parallelism. For this purpose, two alignment plates 24 and 26, as illustrated by Fig. ~~7~~ 10, are located at different z-axis

coordinates. Each alignment plate may be inserted into the beam path at its own precise position downstream of the coarse collimator and the fine-control collimator. Preferably one alignment plate can be inserted at the target plane, but mechanical conflicts may preclude this placement.

As shown by Fig. ~~7~~ 10, each plate 24 and 26, contains a row of aligned holes set at known positions; these appear as multiple slot holes and a central round hole. The central round hole is intended to be positioned precisely on the z-axis; and this may be verified (and if necessary, error adjusted out) by means of the autocollimating telescope or laser used to identify and define the z-axis.

The remaining slot holes are disposed in the y=0 plane at different, but accurately known, x-axis coordinates. These slot holes are preferably a regular linear array; and for illustrative purposes, one can consider each of the two plates to have an identical linear array of seven holes, as illustrated by Fig. ~~7~~ 10.

Each alignment plate 24 and 26, in turn, is placed in the path of the ion beam while the beam is scanned at a suitable amplitude and with a suitable waveform, typically a sawtooth pattern waveform. The scanned ion beam is thus passed over and through each hole of the alignment plate in turn. Then, as the scanned beam becomes transmitted through each individual hole in the two alignment plates, each transmitted ion beam appears as a current pulse which is subsequently collected in a Faraday cup (or cups); its current is measured; and the moment of the collection of the different current pulses is recorded as a function of time within a scan cycle. For preference, a single Faraday cup ("FC" in Figs. ~~1A~~ 3, ~~5~~ 8, and ~~6~~ 9 respectively) is used, which is permanently mounted behind the target plane TPI.

The difference between the times of the arrival of a current pulse through the first hole of the first alignment plate when compared to its arrival at the first hole of the second alignment plate is proportional to the error of the x-direction of the ions at this point in the scan cycle. With

seven holes in each alignment plate, seven different values of x' at seven different timed points in the first half of a scan cycle can be measured; and the same process can be performed in reverse for the second half of a scan cycle.

The errors recognized after measuring the initial non-parallelism may be then corrected by providing a magnetic field whose y-axis component varies as a function of x, since the field component B_y is responsible for deflecting the trajectories within the x-z plane.

Measuring the Y' Error:

To achieve precision, one must also measure the y' error, which would require a uniform B_x component to correct it. This y' error should be almost constant in time, because of the symmetry of the system in the y=0 plane, as discussed above. One can compensate any static error in y' by providing a uniform magnetic field component, B_x, either by using the y-axis steering coils of the preferred fine-control collimator; or, in an adjacent zone at a different z-coordinate, by using a discrete magnetic steering device.

The simplest way of both measuring such a y' error and correcting it is to place both alignment plates 24 and 26 with their range of aligned holes in the beam simultaneously, preferably after correcting the errors in the x' angles. The total average beam current will vary if the component of beam motion in the y-direction is varied; and the maximum transmitted current must occur when the y-component of motion is zero.

To obtain the best sensitivity of detection for y' errors, the beam should be passed through a plate having two holes with small y dimensions, a size for which the slot holes of Fig. ~~7~~ 10 are not suitable. Also, it is possible to halt the scanning with the beam positioned over the central hole of the alignment plate, thereby achieving the desired sensitivity. Other alternatives are: to observe only the current through the central hole in each alignment plate – either by

A variant of this method may be performed using the modified system arrangements described previously and illustrated by Figs. ~~5~~ 8 and ~~6~~ 9 respectively herein, in which the second alignment plate is inserted into the beam and the pulse ion charge passing through each of the long slots and received by the single large Faraday cup may be recorded. Such a technique requires (i) that the slot holes be taller than the beam; (ii) that the pitch of the slot holes exceed the beam width; and (iii) that the width of the slot holes be accurately identical. If used in this manner, the central hole would preferably be identical to the other holes.

Technique 2:

A second method would provide a traveling Faraday cup, which can be traversed across the beam at or near the target plane in the x-axis direction. The ion charge at multiple locations is integrated for one or more scan cycles.

This technique has the advantage that since one Faraday cup is used, systematic differences (which could distort the profile) are eliminated. The technique is also capable of very fine resolution; however, it is to be hoped that the dosing profile contains no very abrupt features.

Technique 3:

The third and preferred method, capable of very fine resolution, is to remove the two alignment plates from the ion beam; and then measure the beam current in a single, large Faraday cup as a function of time. To convert this data to a profile showing average dose rate versus position requires some additional information, which has already been obtained during the initial empirical measurement of non-parallelism performed earlier.

Firstly, one must have data identifying the relationship between time in the scan cycle and x-position of the beam centroid. This relationship was measured at seven points in each direction of the beam scan using the second alignment plate during the measurement of parallelism.

Secondly, one must have data identifying the relationship between scan position and scan velocity, since the dose rate, J_x, is proportional to I_x/v_x, where I_x is the current measured at position x in the Faraday cup (the position being obtained by interpolation) and v_x being the beam scan velocity. Clearly, if one knows the position of the beam at seven precise times, one can interpolate the data to determine the velocity; or to obtain greater accuracy, one can fit a polynomial to the data, differentiate, and obtain an accurate profile of the velocity.

Using this procedure, the value of J_x can be determined at any position within the scope of the measurement.

Having obtained the ion doping profile by any of the above methods, it is now possible (via well known methods) to calculate a desired and pre-selected modification to the scan waveform applied to the scanner that would compensate the non-consistency in the doping profile, thereby improving the profile uniformity with which implants can be performed.

VII. A Preferred Method for Adjusting And Aligning the Parallelism Of A Scanned Beam And For Controlling The Error Variation Of The Angular Spread Within The Ion Beam

Initially, an ion beam is generated in a vacuum system by well-known methods. After mass-analysis to ensure purity, the beam is scanned using a scanner device which can take different structural forms.

In one embodiment, the scanner device comprises a pair of approximately flat electrodes ("SD" in Figs ~~5~~ 8 and ~~6~~ 9 respectively), 150mm in z-dimension, with a tapered gap in the x-axis

Optical And Mechanical Alignment:

The method of the present invention increases the parallelism of a scanned ion beam. To achieve this purpose, an autocollimating telescope100 is rigidly attached to the coarse collimator, such as a dipole magnet (as in Figs. ~~5~~ 8 and ~~6~~ 9). The autocollimating telescope can either be arranged to look through a precision window into the vacuum; or, alternatively, be attached in place of a removable flange when the vacuum system is vented.

The optical axis of this autocollimating telescope is *defined* to be the z-axis of the coordinates system; and all other pieces of equipment must be aligned to this defined axis. The telescope itself provides the means of measuring any alignment errors of the physical beamline components. In particular, a person may look through the telescope at a silicon wafer mounted on its holder in the target plane on the means provided for passing the wafer through the beam. The reflection on the wafer surface of the light source (provided as part of the autocollimating telescope) may be observed through the eyepiece of the telescope; and correct alignment of the wafer surface normal to the z-axis is confirmed when the image of the light source becomes centered within the crosshairs of the telescope.

The alignment of the ion beam to the z-axis cannot be directly observed by means of the telescope, and is instead measured in the following manner: As previously described, two alignment plates are provided on movable mechanisms so that each may be inserted individually into the beam path, or retracted. For equipment intended to implant 300mm sized silicon wafers with ions, seven (7) slot holes of 3mm width on a pitch of 50mm are to be used for each plate. The height of the slot holes is greater than the largest beam height that is expected; and it is desirable to restrict the beam height to less than 20% of the substrate height for reasons of efficient beam utilization. Accordingly, the slots are 60mm high. The central hole may differ for reasons already described herein as well as for easy identification. The mechanism in each

instance is adjusted so that the centers of the slot holes lie approximately in the plane y=0, and the central circular hole can be viewed in the telescope and adjusted to lie precisely on the z-axis. Following this alignment, a vacuum can be re-established within the implantation system.

A single Faraday cup, with dimensions 400mm wide by 70 mm tall, is provided to receive all or most of the scanned beam; and the Faraday cup is magnetically suppressed to prevent slow ions and electrons from distorting the measurement of the current of fast ions. The Faraday cup is preferably permanently located behind the plane of implantation to receive all of the ion beam that has not been previously intercepted by other apertures and objects. With either alignment plate placed in the beam pathway, a series of current pulses can be measured as the beam traverses the slot holes, and a fractional part of the beam briefly reaches the Faraday cup.

Also, in accordance with the modified system shown by Fig. ~~5~~ 8 , the alignment plates are individually located, one being situated in front of the implantation plane and the other behind it. Preferably, one plate is located in the implant plane. Since the plate at the plane is only used before an implant, and not during the actual implantation process, this plate can (and must) be withdrawn during the implant process. Nevertheless, by placing this plate in the implant plane, the beam position versus time during each beam scan cycle of the implant process is explicitly determined *in the implant plane;* whereas, with the modified conventional arrangement, such information can only be determined by interpolation.

Accordingly, the first alignment plate is inserted into the beam and the second is retracted. The current in the Faraday cup is then measured, via an electronic current-to-voltage converter, on a digital oscilloscope. . This will determine, with a precision of better than 500nsec, the time the beam centroid is scanned across each slot in either plate. Fig. ~~8A~~ 11A shows a typical waveform that may be expected; and Fig ~~9~~ 12 graphically illustrates how the angle of the

beam centroid may be calculated from measurements made using the two alignment plates shown by Fig. ~~7~~ 10.

Also, if the central hole of the alignment plate is small, the current transmitted through this hole is significantly less than that transmitted current pulse through the slot holes of the alignment plate, and this can aid in identifying the beam position. The beam should be scanned through a distance exceeding the target width by an adequate but not excessive margin, which is slightly greater than the instantaneous width of the beam 70 and which should preferably not exceed 60mm in breadth. This overscanned beam is shown as item 72 in Fig. ~~1A~~ 3.

Finely Controlled Collimation:

The method for increasing parallelism preferably employs the fine collimator/steerer as described previously herein and shown by Figs. ~~1A~~ 3 and ~~1B~~ 4. The preferred construct comprises two parallel multideflector sequence arrangements which are located symmetrically about the scanned beam at equal and opposite y-axis coordinates (+/- g) and which extend parallel to the x-axis in its positive and negative directions. Each multideflector sequence comprises a series of electromagnetic deflectors (preferably identical) located such that the beginning of each deflector is aligned with one of the slots in the nearest alignment plate, and the end of each deflector is aligned with the next slot hole in the plate. The number of coil deflectors positioned in series on each support bar in the cascade should be one less than the number of holes in each plate. However, it is deemed advantageous also to provide x-axis steering coils which are positioned beyond the slots of the alignment plate.

The outermost slots of the alignment plate are preferably aligned at or near the limits of the zone in which it is desired to improve the parallelism of the beam, the start and the end of

each deflector in the cascade being aligned with a slot hole in the plate. The positions of the outer x-axis steering coils are less critical.

The separation gap distance existing between the first and the second multideflector sequence arrangement must exceed the maximum expected beam height by a safe margin; and these may be located outside the vacuum chamber. Accordingly, a separation gap of 100mm is preferred. It is advisable to use hollow conductor for the individual windings on the support bar for efficient water cooling, as this allows the deflector thickness to be minimized. It is expected that the maximum required correction is +/- 0.5 degrees.

The Steps Comprising The Method Of Operation:

The method of operation comprises the following steps, which are illustrated and explained by the flow diagrams shown by Figs. ~~11~~14 and ~~12~~ 15:

Once the system's mechanical alignment is correct, an ion beam is tuned and analyzed. With the scanner set to a constant deflection potential, this beam is transmitted through the central holes in the insertable alignment plates, which may require a small adjustment to the constant deflection potential to steer the beam accurately along the desired path into the corrector magnet. The corrector magnet is adjusted to maximize the beam transmission through the central holes of the plates into a Faraday cup.

To maximize this transmitted beam current, the x-axis steering coils of the fine-control construct may be suitably energized with suitable dc currents. These currents can be adjusted to maximize the transmitted beam current, thereby ensuring correct alignment of the unscanned beam centroid.

The beam is now scanned with a sawtooth waveform applied between the scanner plates ("SD" in Fig. ~~6~~ 9). One alignment plate is inserted in the beam, and the other plate is removed. The amplitude is adjusted until the current received in the Faraday cup, when viewed on a digital oscilloscope (not shown) appears as shown in Fig. ~~8B~~ 11B, at which point the scan amplitude is sufficient, but not excessive. The oscilloscope scan should be synchronized to the scanner waveform.

The digital oscilloscope is used to determine the time at which the ion beam centroid passes each of the slots in the first alignment plate. At this stage, the first alignment plate is withdrawn, the second alignment plate is inserted, and similar data is recorded.

The Underlying Theory Of Operation:

Mathematically, one can denote the time of beam passage through the first hole in the first sample plate by the symbol t_{101}, and the time of beam passage through the first hole in the second alignment plate by the symbol t_{201}, and so on. Thus, the seventh hole of the first plate is denoted by the suffix 107.

Similarly, the return scan data points are numbered t_{108} through t_{114}, denoting data points 8 through 14, with point 14 denoting the final passage of the beam through hole 1. The distance between the two sample plates is "d", and the beam is known to be traveling with a velocity "v". The pitch of the holes is denoted by the symbol "p", which in this embodiment has a value of 50.0 mm.

The x' angle denoting the direction of the beam centroid when passing through hole 1 of each plate is given by the following expression:

$$x'_1 = (t_{201}-t_{101} - v/d)*v_s/d$$

Presuming that the separation distance between the ferromagnetic support bars is 2g, then $\Delta B_y = \mu_0 nI/g$, where I is the total current flowing in each coil, and n is the number of turns. ΔB_y is the change in B_y across the x-dimension of each coil pair, so if B_y=0 (as assumed) at the center, then the field in line with the next slot in the plate is defined. It is a simple matter to extend this process to each slot position in turn.

Depending on the distribution of ampere-turns on each side of the x=0 plane, the magnetic scalar potential at the center of the support bar will not be zero; and as a result, the field $B_y(0)$ at the center will not be zero as assumed. This will cause the whole beam to be steered systematically in either the positive or negative x-direction. This steering effect can be compensated by passing a suitable current through the x-axis steering coils. This adjustment may be pre-calculated or by repeating the steering correction made at the outset.

Figure ~~10~~ 13 illustrates the reduction in non-parallelism that may be obtained using four pairs of coils, and five sampling slots in each aperture plate. The attenuation is of the order of $1/n^2$, where there are 2n active coils, so n=4 and the attenuation is of the order of 1/16.

Orthogonal Effects On Beam Collimation:

In general, the ion optical properties of a dipole magnet used in prior art systems to correct the parallelism of scanned ion beams have an undesirable property in that the focusing of the instantaneous ion beam, and therefore the angular spread Δy', is a function of the scan angle. It is desirable to minimize this effect in order that the size and particularly the angular distribution of the ion beam remain reasonably constant as the beam is scanned across the implanted target.